TASK QUARTERLY 2 No 2 (1998), 205-213

COMPUTATIONAL FLUID DYNAMICS METHODS IN TURBOMACHINERY

TADEUSZ J. CHMIELNIAK

Institute of Power Machinery
Silesian Technical University
Konarskiego 18, 44-100 Gliwice, Poland

Abstract: This paper aims to present a general view of the flow problems in turbomachinery and the current levels of numerical methods for solving these problems. The flow models used for modelling phenomena in blade cascade are presented. The models of turbulence are discussed. A variety of examples of turbomachinery problems, such as steady, unsteady flows, multiphase and multicomponent flows, blade cooling are described. The actual research fields of computational fluid mechanics are presented.

1. Introduction

The flow of gases in the flow paths of turbo-machines is extremely complex. It is three-dimensional, viscous with zones of laminar, transient and turbulent motion. Various vortex structures are generated, in the highly loaded ducts shock waves are formed, which interact with zones strongly affected by viscous stresses. The absolute velocity in the stage system is always unsteady. In the case of a flow which is characteristic for non-adiabatic heat engines (cooling down of the stator blades, rotor blades, casings, rotor disks and other elements) these phenomena describe the conjugate initial-boundary value problems.

The development of numerical methods in fluid mechanics, as well as the constantly growing information concerning the phenomena of the dissipation of energy in fluid-flow machines have led to the development of more and more reliable methods of calculation and algorithms of aerodynamic optimization. This progress results in the resignation from simplifications in the mathematical description of observed phenomena, the possibility of taking into account the actual geometries, a better description of the properties of the working media and the application of advanced procedures in the analysis and processing of the results of calculations.

The question arises which classes of analysis and synthesis of turbomachines can be solved at present providing information about the physics of flow processes and practical constructional premises. It is the aim of this paper to discuss this problem.

2. Flow Models

2.1. Equations of Motion

The equation of continuity, Navier-Stokes equations and the equation of energy compose a set of equations which fully models the properties of the real flow of gas in fluid-flow machines and devices. They reflect the fundamental physical conservation laws which have been formulated for the Newtonian fluid meeting the assumptions concerning a continuous medium. In general, it may be expressed like this [1]:

$$\frac{\partial f}{\partial \tau}+\alpha(f)=\mu \tag{1}$$

Concerning the gradient form of the equations of motion this looks like that:

$$\alpha(f)=\frac{\partial}{\partial q^k}\alpha^k(f) \tag{2}$$

The equations of motion may also be expressed in a quasi-linear form, and then (1) we get:

$$\frac{\partial f}{\partial t}+Pf=R, \quad P=\frac{\partial \alpha^k}{\partial f}\frac{\partial}{\partial q^k} \tag{3}$$

The operators (ι) and P depend on the assumed mathematical model of the described flow and e choice of the vector of dependent variables f. In the absolute coordinate system fι r the "conservative" variables $f=\{\rho, \rho c, E\}^T$ in equations of motion the source term $\mu = 0$ (in the absence of a field of body forces). This property is preserved both in the case of orthogonal and not orthogonal coordinate systems. Therefore, this form ˙ most often used to formulate initial-boundary value problems for the present stage of development of fluid-flow machines. In a relative coordinate system it is not possible to omit the source term resulting from Coriolis and centrifugal acceleration [1-4].

The flow in heat turbines belongs to the family of internal flows, Figure 1. In order to model them various steps of physical and mathematical simplifications are applied [1, 3]. The most general model comprises: a complete set of conservation laws, initial and boundary conditions, as well as equations describing the properties of the working media. In the first stage we pass from Navier-Stokes equations to Reynolds equations averaged in time and locally in space, which requires the introduction of turbulent stresses.

In Euler approximation equation (1) is only hyperbolic (both for M > 1 and M < 1, M Mach number). Disturbances (information) are in this case passed along the bicharacteristics, and the number of imposed boundary conditions (the number of physical boundary conditions) is the number of bicharacteristics connected with the

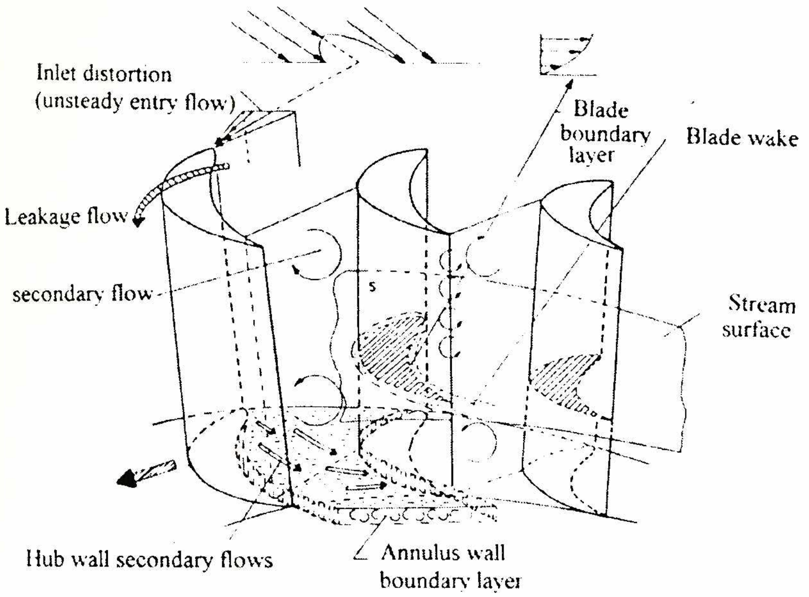

Figure 1. Nature of internal flow in blade passage

normal vector of velocity to the boundary (S_i) becoming part of the area in which the flow is being investigated. The other conditions preset in order to solve the given initial boundary problem are numerical conditions.

Due to the presence of diffusive elements in the equations of momentum and energy, Navier-Stokes equations get a more complex mathematical structure than Euler equation. The equations of momentum and energy are parabolic equations versus time and space, and elliptical equations versus the spatial co-ordinates of stationary flows. The equation of continuity is hyperbolical for both cases. In the case of actually occurring situations the initial boundary problems (or boundary problems) formulated in relation to a full set of equations of conservation are hybrids in their character: parabolic-hyperbolic in the case of non-stationary flows and elliptically-hyperbolic in the case of stationary phenomena. This fact renders it difficult to discuss the boundary conditions while taking into account the general conditions of the flow fluids.

2.2. Modelling of Reynolds Stresses

In order to average Navier-Stokes equation in compliance with Reynolds or Favre conception we must determine the tensor of Reynolds stresses as a function of independent variables. These dependencies vary in their structure and have often been called models of turbulence. They may be divided into two groups [1]. To the first group belong models introducing the notion of turbulent viscosity, the crucial notion of Boussiesque hypothesis. The fundamental basis in the classification of models i this group (nowadays called methods of the first order) is the number of differentia equations of transport of definite quantities which are characteristic for the turbulen flow. Thus we may speak of zero-equation (algebraic), one-equation, two-equatio models etc. Models of the second order are formulated making use of transpor equation for Reynolds stresses. From the various ways and methodologica assumptions applied to determine the respective terms to this equation there resul various concrete propositions of closing hypotheses [1, 2, 5].

Due to the complex character of the flow of fluids through the ducts of turbo machines none of the models of turbulence set up so far may be considered to b universal.

From among the group of algebraic models of turbulence the most often applie one is Baldwin-Lomax model (B-L) [6]. The simplified physical premises, basing o which zero-equation models have been developed (among them the model B-L) mak it possible to obtain satisfying solution only in the case of simple flow structure Basing on numerous investigations and calculations [6, 7] we may say that:

- the considered models are adequate in the case of two-dimensional flows of com pressible fluids with moderate pressure gradients
- they may be applied for three-dimensional boundary layers with slight secondar flows,
- they are not of much use in the case of flows with strong curvatures of the strea line, Coriolis acceleration, centrifugal acceleration and seperations of the bound ary layer,
- they are of no use for the intake of secondary flows generated by pressure gradi ents, turbulence and flows with considerable variations of tangential stresses,
- they do not describe satisfactorily the effects of shock waves with the boundar layer.

In the case of two-dimensional flows with moderate pressure gradients no effec were to be observed when they were replaced by "physically" more advanced model Quite good results have been obtained in investigations of a flow with positiv pressure gradients flows affected by shock waves in a zone with a boundary layer (i the two-dimensional geometry) applying Johnson-King's model [8].

For flow structures which are characteristic for turbo-machines several tw equation models have been developed, payng much attention to an improvement o the k – e model. In spite of a considerable progress if compared with zero-equatio models, this model does not warrant good results, either, concerning all the possibl flow structures in the ducts of fluid-flow-machines. For two-dimensional flows th mean velocity profiles and main characteristics of turbulence can be calculated rathe accurately. In the case of the 3-D geometry it is generally not possible to attain a hig accuracy as far as intensive secondary flows and shock waves are concerned. This model renders bad results in investigations on the flow of liquids through the rotating ducts with curvatures and separation.

From among various ways of enlarging the range of application of this kind of models attention ought to be drawn to its combination with algebraic Reynolds stress models as suggested by Rody [2] and further developed in [9] and [10]. This model takes into consideration the influence of curvatures and accelerations at a relative flow.

As the equations of transport of Reynolds stresses are rather complex, they are rarely used in investigations of turbo-machines. The available results indicate, however, that they are highly promising [2].

3. General Analysis of the Solved Problems

3.1. Numerical Schemes and Algorithms

From among the three main groups of methods finite difference, finite-elements and finite-volumes methods the latter one forms the fundamental basis of many codes of calculations (Euler and Navier-Stokes equations) applied in turbo-machines. In the case of compressive flows (particularly in areas of transonic flows) for the approximation of convective terms "upwind" methods are widely used, mainly those of the Godunov type, which apply Riemann problems for the purpose of determining the parameters between the nodes of the numerical grid. These methods are also known as methods of "Flux Difference Splitting" - FDS. In contradistinction to finite differences, schemes of the "upwind" type take into account the characteristic directions of the propagation of disturbances in the flow. If additionally such procedures are applied as limiting functions, schemes with Total Variation Diminishing properties, they allow a highly accurate determination of such distinct phenomena as shock waves and tangential discontinuities without unnecessary numerical oscillations, Figure 2.

Diffusive terms are usually approximated in a way similar to parabolic equations.

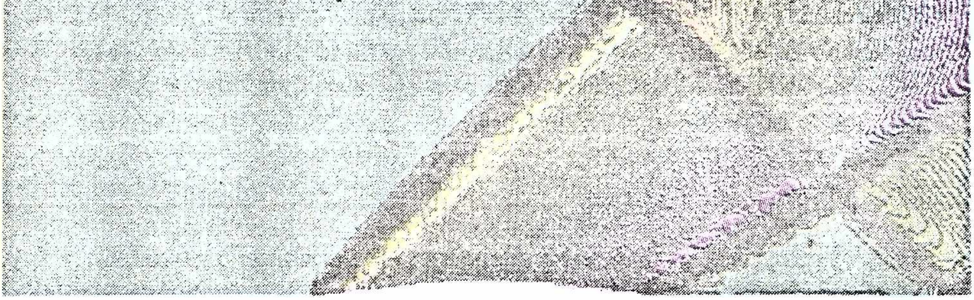

Figure 2. *The shock configuration by flow around the obstacle*

A discretisation relative to time is obtained by the application of Lax-Wendroff formulation, Beam and Warming schemes or Runge and Kutty method.

A review of numerous differential schemes and calculation algorithms has been provided in [1] and [3].

3.2. Stationary Flow

Investigating the stationary flow in the individual ducts of turbo-machines (heat turbines and compressors) with intensive discontinuities much information can be obtained when integration algorithms of Euler equations are used. Both the localisation and intensity of the discontinuities have been correctly simulated for complex geometries. Also the application of this type of codes in the optimisation of ducts has made it possible to create new constructions of blade systems, Figure 3. In the case of stationary flows generally also commercial codes are applied based on Navier and Stokes equations and selected models of turbulence. Thanks to their application it is easier to understand the processes of the generations of secondary

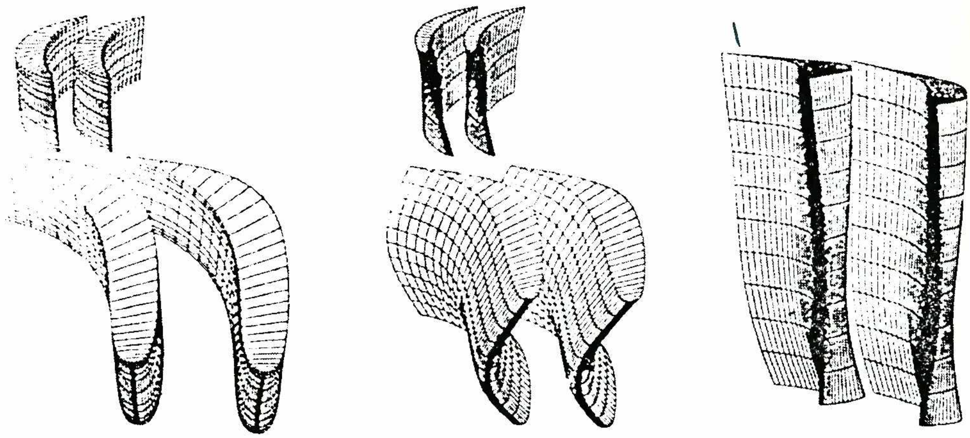

Figure 3. An example of new blade constructions

flows and the energy analysis of cascade flows [11].

Codes which are based on Euler equation and combined with correlation describing the losses of mechanical energy constitute the basis for discussions concerning the flow characteristics for stage groups and whole flow systems.

In the range of three-dimensional stationary flows further investigations should aim at the authentification of simulations of the dissipation effects of and thermal load (including non-adiabatic flows).

3.3. Non-stationary Flow

The ability to determine quantitatively non-stationary effects in turbo-machines brought about by the mutual interactivity of the respective blade-rim is of fundamental importance for the improvement of the energy conversion efficiency. Periodical disturbances caused by these interactions comprise both large scale duct structures of secondary flows and small-scale vortices of aerodynamic traces, as well as thermal disturbances. The analysis of such flow phenomena generally requires sofisticated codes of numerical integration of Navier-Stokes non-stationary equations. The transport of secondary fluids through the impeller (rotor) duct can in general be easily recognized basing on Euler non-stationary equations, particularly if we do not take into consideration the evolution of the boundary layers. In other cases (among others: in the case of prediction the processes of separation, the effect of shock waves on the boundary layer etc.) complete flow models must be applied. The algorithms at our disposal do not quite allow a reliable discussion about these problems. What is needed, is some progress in the physical modelling of the interaction between disturbances and discontinuities on the one hand, and the flow zones with an essential influence of viscosity on the other.

3.4. Multiphase and Multicomponent Flows

The solution of problems concerning cavitation, dust and water erosion, the condensation flow in steam turbines and the flow accompanied by combustion requires a continuous improvement of the methods of investigating multicomponent and multiphase flows. In the case of some new energy techniques these problems acquire additional importance. This concerns particularly flows in gas turbines, in installations in which coal is burned directly, in combine cycles integrated with coal gasification, as well as in pressure-combustion systems. Transonic flows with condensation are characteristic for the last stages of modern steam turbines. The methods of their solution usually comprise an algorithm of integrating unsteady equations of conservation Laws (in Euler formulation) and the liqiud-phase particles equation (in Lagrange formulation). The equation of the growth of water drops takes into account changes of the values of over-cooling in time, as well as the actual properties of steam. The analysis of flows connected with combustion is of essential importance for the improvement of boiler processes, combustion chambers and gas turbines.

3.5. The Cooling of the Blade System

Aircraft engines and stationary turbines are nowadays cooled down by means of air supplied by compressors. Techniques of closed steam cooling (in gas-steam systems) are presently being investigated; simulaneously the application of thermosiphons and heating pipes in cooling systems are investigated.

In numerical calculations this problems is modelled by investigations concerning the flow and exchange of heat in stationary and rotating straight and U-shaped ducts, Figure 4.

The fundamental problem is the modelling of turbulence, as the flow structure and the influence of curvatures and the Coriolis force on the stability of the hydraulic and thermal temperature boundary layer is rather complex. An important trend is the investigation of the sensitivity of the respective models to changes of the fundamental parameters of the flow [12]. The problem of the right choice of a model is far from being solved. The present state of researches suggests the necessity of further

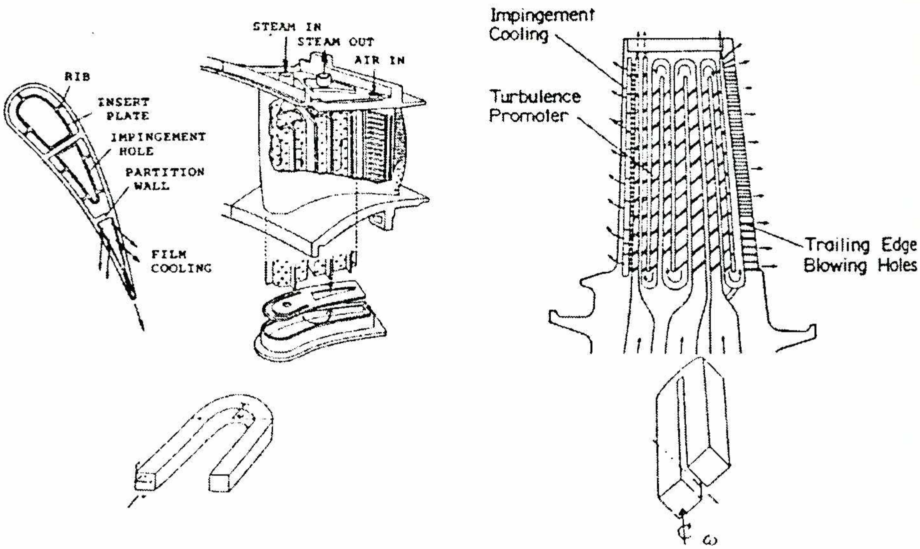

Figure 4. *Cooling of the gas turbine blades*

investigations on combined k – ε models and the algebraic model of Reynold stresses (ARSM) and also of wider investigations concerning the application Reynolds stress model in the case of such complicated flow structures.

Analysing the extermal cooling (flow around the blading) considerable difficulties are encountered in the case of non-stationary transonic flows and the application of film and diffusion cooling. Classical models of turbulence, including ARSM, do not comprise all the phenomena characterising this flow, therefore a further progress will be possible only when models of the second order have been developed and applied.

4. Conclusions

The available algorithms for the solution of Euler and Navier-Stokes equations enable us to obtain a lot of quantitative and qualitative information about phenomena connected with the conversion of energy in turbo-machines.

Researches in the field of fluid mechanics and heat exchange, as well as of combustion are concentrated at present on the following problem:

- attempts to find adequate models of turbulence comprising all the fundamental processes and phenomena (laminar-turbulent transitions, the effect of shock waves, separation, the influence of curvatures, Coriolis acceleration, boyanle efect, the lack of isotropy etc.),
- the development of fluid mechanics and thermodynamics of multiphase and multicomponent flows,
- non-stationarity of the flow in blade systems,
- the development of new schemes of integrating Navier-Stokes's equations,

- the generation of self-adapting and non-structural calculation grids,
- the elaboration of algorithms for the visualisation of flows.

References

[1] T. Chmielniak: *Przepływy transoniczne*. Ossolineum, Wrocław, Warszawa, Kraków, 1994

[2] B. Lakshminarayana: *Fluid Dynamics and Heat Transfer of Turbomachinery*. John Wiley and Sohn, Inc. New York, 1966

[3] Ç. Hirsch: *Numerical Computation of Internal and External Flows. Vol. 1, 2*, Wiley. New York, 1988, 1990

[4] W. Wróblewski: *Numeryczne metody rozwiązania równań Eulera i Naviera-Stokesa. Materiały wykładowe IX Szkoły Letniej Mechaniki Płynów*, Nowa Kaletka, 1996

[5] J. Elsner: *Turbulencja przepływów*. PWN, Warszawa, 1987

[6] H. Benetschik: *Numerische Berechnung der Trans-und uberschal-Stromung in Turbomaschinen mit Hilfe eines impliziten Relaxationsverfahrens. Dissertation*, RwTH Aachen, 1991

[7] B. Lakshminarayana: *An Assessment of Computational Fluid Dynamic Techniques in the Analysis and Design of Turbomachinery — The 1990 Freeman Scholar Lecture. Trans. of ASME, J. of Fluids Eng. Vol. 113*, September 1991, pp. 315-349

[8] D. A. Johnson, L. S. King: *A Mathematically Simple Turbulence Closure Model For Attached and Seperated Turbulent Boundary Layers. AIAA Journal, vol. 23, 11*, 1985

[9] J. M. Galmes, B. Lakshminarayana: *Turbulence Modelling for Three-Dimensional Turbulent Sher Flows over Curved Rotating Bodies. AIAA Journal, vol. 22, No1*, 1984

[10] J. Lao, B. Lakshminarayana: *Navier-Stokes Analysis of Turbine Flow Field and Heat Transfer. J. Propulsion and Power. Vol. 11, No2*, 1995

[11] W. N. Daves: *Current and future development in turbomachinery CFD. 2 nd Conf. On Turbomachinery-Fluid Dynamis and Thermodynamics, Antwerpen*, 5-7. 03. 1997

[12] B. E. Launder, H. Iacovides: *CFD Applied to Internal Cooling. VDI Berichte 1195, pp. 1-34*, 1989